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Integrated evaluation of embodied energy, greenhouse gas emission and economic performance of a typical wind farm in China

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ABSTRACT

An integrated evaluation of embodied energy, greenhouse gas (GHG) emission, and economic performance of a wind power generation system in China was conducted, using a range of indicators. Energy and GHG emission costs per unit profit are proposed as goal functions for potential low-carbon, high-efficiency optimization of the wind power generation system. Results show that the energy efficiency and GHG emission per energy output of the system are 0.034 MJ/MJ and 0.002 $kgCO_2$-eq/MJ, respectively. Compared with other power generation systems, wind power is more competitive in terms of both energy savings and GHG emission reduction. If wind turbine recycling in the dismantling phase is taken into consideration, 46.7% of energy will be saved, with a material recycling rate of 0.467. Scenario analyses are done to investigate economic feasibility, from the perspective of investors and government. Finally, suggestions are provided to shed light on wind industry development in China.

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Contents

1. Introduction

China is experiencing rapid economic growth, which is fostered by intensive fossil fuel consumption. However, this development mode is being gradually threatened by declining resource reserves and environmental capacity. Tremendous greenhouse gas (GHG) emissions from the combustion of fossil fuels and unsatisfied

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energy requirements have forced the country to seek and adapt to environmentally friendly and renewable alternatives for sustaining an increasing energy demand. To this end, the government must place more emphasis on renewable energy in future energy structures.

Renewable energy sources are not exploited equally, as some are more economically and environmentally viable than others. Wind power, which is currently the favourite of environmentalists, is believed to be the most likely renewable energy source for replacing fossil fuels in electricity generation of the 21st century [1]. According to an evaluation report by the China Meteorological Administration, the wind resource in the country is 0.7–1.2 billion kW, of which 0.6–1 billion kW is inland, and 0.1–0.2 billion kW is offshore. Wind power generation can therefore reach 2.21×10^{12} kW h per year, which is almost 17% of total national electricity generation in 2050, the third largest power source in the country [2].

Since the first 55 kW wind power generation system installed in Shandong province in 1986, the Chinese government has paid great attention to the utility of wind resources. As shown in Table 1 and Fig. 1, relevant policies have been supporting the momentum of the wind power industry in the country, whose development can be divided into three stages.

In the infancy stage (1985–1996), the national government began to emphasize energy saving and encouraged the demonstration of small-scale wind farms. In this phase, the government only provided a small part of the financial support, while donations and loans from abroad were largely used to guarantee wind farm construction. The installed capacity of wind power therefore fluctuated erratically, as shown in Fig. 1. However, a great deal of experience was gained in this stage, which laid a necessary foundation for later development.

During 1997 to 2004, wind farm construction experienced its preliminary development, with established regulations based on economic, environmental and technical aspects (Table 1). However, China was in transition to a competitive market. The high cost of the wind power made it inferior to traditional coal-fired electrical power, which hindered its development in this stage. Fig. 1 shows that the growth rate of installed wind turbine capacity remained relatively small, and even had a declining trend.

Table 1
Policies on wind power development in China in different stages.

Stage	Policies
1985–1996	Electricity Act of People's Republic of China
	Management Regulations on the Grid-connected Operation of Wind Farms
1997–2004	Energy Conservation Law of the People's Republic of China
	Notice of the State Council on Adjusting Policy of Import Equipment Taxation
	Some Opinions About the Further Promotion of Wind Power Development
	Interim Measures of Management of Land use of Wind Farm Construction Project and Environmental Protection
	Guidance on Speeding up Localization of Wind Power Technology and Equipment
	The 10th Five-Year Plan for New and Renewable Energy Industry
	Outline on the Preliminary Construction Work of the National Large-scale WindFarms
2005 till now	The Renewable Energy Law of The People's Republic of China
	The Notice of the National Development and Reform Commission on the Relevant Requirements for Wind Power Construction Management
	Regulations on the Administration of Power Generation from Renewable Energy.
	The Tentative Management Measures for Allocation of Prices and Expenses for Generating Electricity by Renewable Energy
	The Provisional Measure on Administration of Special Fund for Industrialization of Wind Power Equipment
	The 11th Five-Year Plan" for the Energy Development
	Notice on Perfecting the Feed-in Tariff Policy of Wind Power
	Renewable Energy Price Subsidies and Quota Trading Notification of the First 6 months in 2009

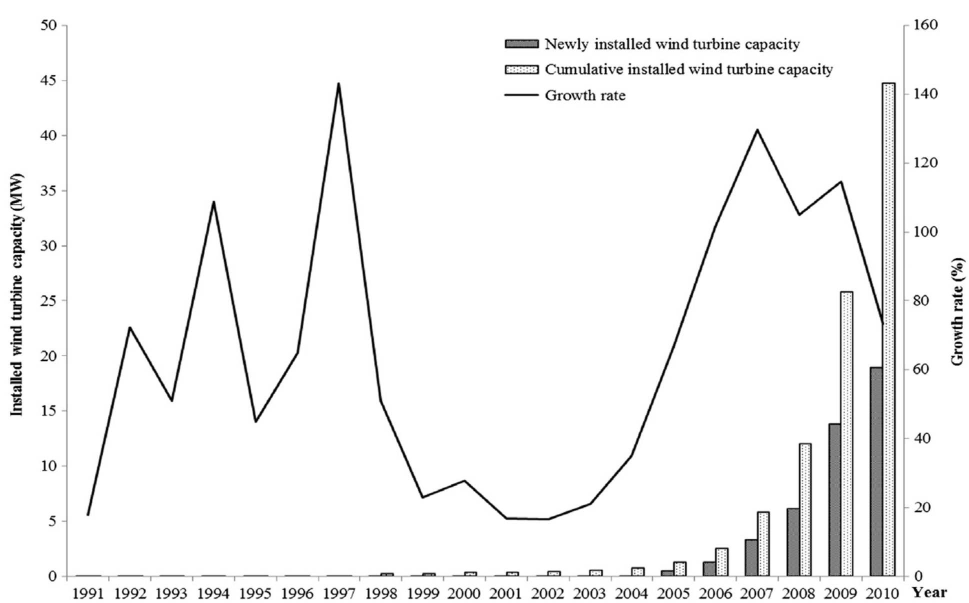

Fig. 1. Installed wind turbine capacity of China from 1991 to 2010 [3,4].

In the current stage (2005 to present), emphasis was placed on improving wind power pricing and a subsidy mechanism. Polices such as "Renewable Energy Price Subsidies and Quota Trading Notification of the First 6 months in 2009", and "Notice on Perfecting the Feed-in Tariff Policy of Wind Power" were issued (Table 1). This resulted in a wind power boom, with annual growth rate 103%.

However, when the total "cradle-to-grave" energy invested in a wind power plant is taken into consideration, a finite quantity of energy consumption and GHG emission is indirectly caused by wind farm projects. Further, high economic costs of wind turbines preclude investments in wind farms, which make the wind power generation system less competitive relative to traditional power generation alternatives. Thus, in pursuit of sustainable development of the wind harnessing industry, an appropriate understanding of the embodied energy, GHG emission, and economic characteristics of the wind power generation system is required.

Several literature reviews are available regarding the evaluation of energy and GHG emission of various renewable energy technologies, especially the wind power generation system. Lenzen and Munksgaard summarized 72 energy and CO_2 analyses of wind-power systems published between 1977 and 2001 [5]. Kubiszewski et al. extended their work by reviewing 119 wind turbines from 50 different analyses, with publication dates from 1977 to 2007 [6]. Raadal et al. presented GHG emissions from wind power generation, based on 63 life cycle assessments (LCAs) published between 1990 and 2010 [7]. Arvesen and Hertwich identified weaknesses and gaps of knowledge that future research could address [8].

Guidelines for calculation of the total energy requirement of electricity generation systems were given in Pilati and Richard [9]. Using their method, Haack [10] calculated the energy cost from a small wind electric system, without considering the energy required to dispose of a generating plant or its waste products. Gürzenich et al. exemplified the calculation of Cumulative Energy Demand and Energy Yield Ratio, and applied these indicators to different renewable energy systems [11]. Lenzen introduced and compared two approaches to monitor energy performance of wind farms, namely, the material-based and cost-based methods [12]. Based on the former method, Ardente et al. evaluated energy performance of a wind farm in Italy [13]. Chen et al. illustrated the high degree of renewability of wind power in China, via a case study of nonrenewable energy cost and GHG emission of a typical wind farm in Guangxi [14]. Weißbach et al. evaluated energy returned on invested for typical power plants representing wind energy, photovoltaics, solar thermal, hydro, natural gas, biogas, coal and nuclear power [15]. Exergetic analysis was also performed to measure the energy conversion efficiency of wind farms [16–18].

Among evaluations of environmental impacts of wind farms, GHG emissions have historically been the focus of attention for LCA research on wind power [5]. Dolan and Heath screened 240 LCAs of onshore and offshore systems, focusing on GHG emissions [19]. Khan et al. presented a detailed LCA of a wind–fuel cell integrated system for application in Newfoundland and Labrador [20]. Martínez et al. evaluated environmental impacts of a wind turbine [21]. Crawford compared energy cost and GHG emissions of two different sized wind turbines, and considered the effect of turbine size on energy yield [22]. Tremeac and Meunier [23] evaluated and compared the environmental impacts of two systems, 4.5 MW and 250 W wind turbines. Wiedmann et al. used a hybrid LCA to account for indirect GHG emissions of energy technologies, using wind power generation in the UK as a case study [24]. Pehnt investigated a dynamic approach toward renewable energy technologies and proved that for all renewable energy chains, the inputs of finite energy resources and GHG emissions are extremely low compared with conventional systems [25]. Martin et al. linked an LCA model of offshore wind utilization with a stochastic model of the German electricity market [26].

The economic performance of wind farms has also been investigated. An overview of economic approaches for evaluation of renewable energy projects has been presented by Menegaki [27]. Munksgaard and Larsen compared the production costs of wind power to central power production based on coal and natural gas, in which the external production costs arise from the emissions of CO_2, SO_2 and NO_x from combustion of fossil fuel, and from noise and visual effects of wind mills were taken into consideration [28]. In the report "The Economics of Wind Energy" [29], economic performance of wind energy was analysed in detail. Ozerdem et al. calculated the net present value, internal rate of return, and economic payback period of wind farm construction [30]. Munksgaard and Morthorst estimated the impact of redesigned tariffs on electricity prices, and assessed whether the new tariffs provide incentive to invest in wind power [31]. Zhang and Zhao investigated the economics of conducting a Clean Development Mechanism (CDM) program at wind farms [32]. Willingness to pay for reducing visual disamenities of future offshore wind farms was elicited by Ladenburg and Dubgaard [33] based on the economic valuation method "Choice Experiments".

Although there are different approaches to embodied energy, GHG emission, or economic performance evaluation of wind power generation systems, most work has focused on quantification of only one or two parameters, e.g., GHG emissions [34–36], energy payback time [37,38], and cost of electricity generation [39,40]. Integrated

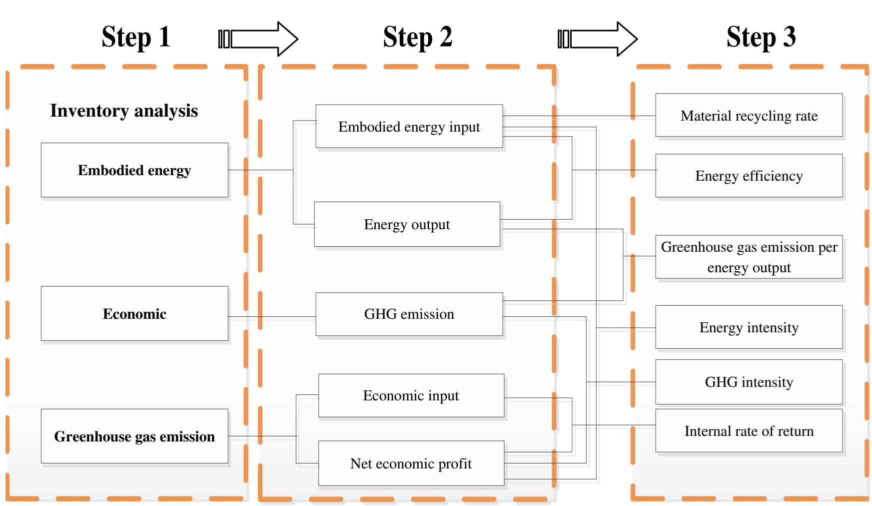

Fig. 2. Embodied energy, economic and GHG emission evaluation framework of a wind farm.

evaluations that reflect overall wind farm performance are still limited. Therefore, a multi-objective evaluation system is necessary to monitor wind farm performance from a systematic perspective. In the present work, we propose an indicator system that is beneficial to a synthesized consideration of embodied energy, GHG emission, and economic factors in system optimization and policymaking. The remainder of this paper is organized as follows. Section 2 describes the integrated evaluation framework and indicators for the wind farm. Section 3 presents an inventory analysis with basic data and system boundary. In Section 4 details the results of embodied energy, GHG emission and economic assessment of the wind farm, along with comparisons of different power generation systems. Conclusions are given in Section 5.

2. Methodology

An outline is proposed to evaluate embodied energy, economic and GHG emission performance of the wind farm (Fig. 2). After clarifying the objective and system boundary, an inventory analysis is performed in Step 1, in terms of embodied energy, economic investment and GHG emission. Step 2 demonstrates results of embodied energy input and energy output, GHG emission accounting, economic input and net economic profit. Based on these, a set of indicators are calculated in Step 3. A multi-objective evaluation framework is thereby established.

Fig. 3. The location of the wind farm in inner Mongolia.

Energy efficiency, GHG emission per energy output, and internal rate of return (*IRR*) are normally used for overall performance analysis. Distinct from these, new indicators of energy intensity and GHG emission intensity, defined as energy and GHG emission cost per unit profit, are proposed as goal functions for potential low-carbon, high-efficiency optimization of the wind power generation system (Fig. 2). The calculation and implication of each indicator are shown in Eqs. (1)–(6).

Material recycling rate (*MRR*) is defined as the ratio of recycled materials in the dismantling phase to total material input based on the embodied energy metric, as shown in Eq. (1).

$$MRR = E_{recycled}/E_{in}, \quad (1)$$

where $E_{recycled}$ is the embodiment of materials recycled in the dismantling stage, and E_{in} is total embodied energy input.

MRR per se cannot be a proper energy indicator for sustainability issues, because it does not include the difference between thermal and mechanical energy based on the second law of thermodynamics. However, *MRR* may describe the material recyclability of a wind farm. The higher the *MRR*, the more materials recycled in the dismantling phase. Since recycled materials can be reused to substitute material input for wind farm construction, energy use and GHG emissions embodied in the construction phase would be reduced.

Energy efficiency (*EE*) has been frequently used as an indicator to calculate the energy budget in earlier studies. In the case of electricity generation, energy intensity entails comparison of the primary energy used in the manufacture, transportation, construction, operation, decommissioning and other stages of a facility life cycle with the amount of electricity generated. The less energy required to produce one unit of electricity, the more efficient the wind farm. *EE* is calculated as

$$EE = E_{in}/E_{out} \quad (2)$$

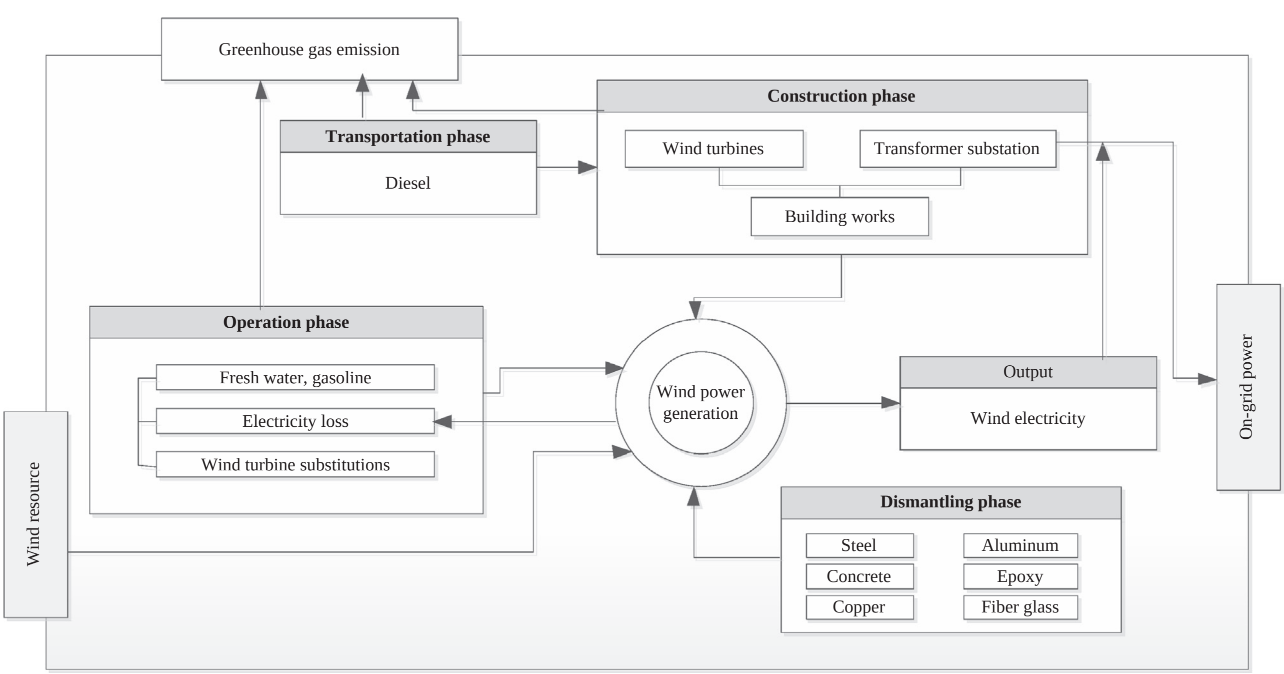

Fig. 4. System boundary of the life cycle of the wind farm.

Similarly, the GHG emission per energy output (ECD) associated with nonrenewable energy cost can be determined as

$$ECD = C_{in}/E_{out}, \tag{3}$$

where C_{in} is direct and indirect GHG emission of the production process, and E_{out} is the total energy of electricity generated by a wind farm.

New indicators of energy intensity (EI) and GHG emission intensity (CI) are defined as embodied energy and GHG emission cost per unit profit, respectively:

$$EI = E_{in}/(B-C) \tag{4}$$

$$CI = C_{in}/(B-C), \tag{5}$$

where C and B are costs and benefits of the wind power project, respectively.

IRR is the value of the discount rate when net present value equals zero, which can be calculated by

$$\sum[C/(1+IRR)^n] = \sum[B/(1+IRR)^n] \tag{6}$$

3. Case study

The concerned wind farm is constructed in Horqin Right Front Banner (HRFB) of Inner Mongolia, which is located at 45°42′07″–47°01′36″N and 119°31′51″–122°52′07″E (Fig. 3). This county has a plentiful wind resource, with average wind velocity 6.98 m/s at 75-m height. There is an average of 23 windy days annually. Wind velocity varies seasonally, stronger in spring (3.4–3.7 m/s) and weaker in summer (2.0–2.5 m/s).

The total installed capacity of the wind farm in HRFB is 150 MW, which is anticipated to be realized in three phases. The first phase, with installed capacity 49.5 MW, is studied here. Based on the characteristic power curve and hourly wind resource data from the study site, annual optimal gross electricity output is 183.5 GW h and on-grid power is 111.7 GW h, with equivalent full-load operating hours 2257 h and capacity factor 0.258. The construction of the wind farm takes 12 months while the operation period is expected to be 20 years.

In total, 33 wind turbines have been installed, each of which has a generating capacity of 1500 kW. With a 100 MV A main transformer, the electricity generated is delivered to a 220 V substation in Chifeng via a booster station on the wind farm.

3.1. System boundary

The input to a wind farm is categorized into three major components: (1) materials such as concrete and steel; (2) equipment, including wind turbine components, i.e., rotors, nacelle, tower and their sub-components, plus transformer substation components (transformers and control systems); and (3) direct nonrenewable energy consumption. We separate the lifetime of the wind farm longitudinally into four different phases, i.e., transportation, construction, operation and dismantling. The entire life-cycle energy flow of the wind farm is depicted in Fig. 4.

3.2. Inventory analysis

3.2.1. Transportation

HRFB has a convenient transportation network, with national highway 111, provincial highway S203 and other thoroughfares traversing the area. Highway transportation is used for wind turbine delivery, starting from the manufacturer in Xinjiang, along highways and national road G111 to the city of Chifeng, and finally arriving at the wind farm via provincial highway S203. The total transportation distance is 4279 km. Transformers are fabricated in Chifeng, 716 km from the wind farm. Other construction materials are purchased in HRFB, as shown in Table 2. Diesel fuel consumption intensity is estimated at 0.05 L/(t km) [14]. Thus, diesel consumption for material transport is calculated at 4.61E+04 kg.

3.2.2. Construction

Inputs in the construction phase include wind turbine components, transformer substation, and energy and material inputs of the building works.

Thirty-three WGT15000A wind turbines with hub height 75 m were installed for the HRFB wind farm project. Rotor diameter is 87 m, with three blades. The wind turbine mainly consists of three parts, the tower, nacelle and rotor. The tower is made of concrete

Table 2
Transportation of major materials.

Category	Unit	Quantity
Wind turbines	t km	1.09E+06
Transformer substation	t km	1.16E+04
Line material	t km	6.45E+02
Tower material	t km	1.85E+03
Concrete	t km	1.95E+03
Others	t km	6.94E+03
Total	t km	1.11E+06

Table 3
Components and parameters of a wind turbine.

Component	Sub-component	Material	Quantity	Unit
Rotor	Hub	Steel	6.20	t
	Blade	Fiber glass	3.90	t
		Epoxy	2.60	t
Nacelle	Generator	Steel	34.56	t
		Copper	8.64	t
	Frame, machinery and shell	Steel	13.50	t
		Aluminum	0.50	t
		Glass	0.35	t
		Polyester	0.30	t
Tower		Steel	129.00	t

Table 4
Energy and materials used in the building works of the concerned wind farm.

Components	Material	Quantity	Unit
Power foundations	Concrete	1.26E+04	m^3
	Steel	1.19E+03	t
Transformer foundation	Concrete	1.26E+03	m^3
	Steel	6.19E+01	t
Distribution equipment	Concrete	4.45E+02	m^3
	Steel	6.40E+00	t
Water		1.00E+04	t
Diesel		5.36E+05	L
Gasoline		1.67E+05	L
Electricity		1.65E+06	kW h

Table 5
Material recycling and disposal principle [41].

Material	Principle of dismantling
Steel	90% recycled and 10% landfilled
Copper	95% recycled and 5% landfilled
Glass fiber	100% landfilled
Aluminum	95% recycled and 5% landfilled
Concrete	100% landfilled
Epoxy	100% landfilled

Table 6
Energy and GHG emission intensity of wind farm materials.

Material	Energy intensity	Unit	GHG intensity	Unit	References
Steel	3.26E+04	MJ/t	1.39E+00	tCO_2-eq/t	[14]
Concrete	6.03E+03	MJ/m^3	5.30E−01	tCO_2-eq/m^3	[14]
Fiber glass	1.88E+05	MJ/t	3.07E+00	tCO_2-eq/t	[14]
Epoxy	4.57E+04	MJ/t	3.94E+00	tCO_2-eq/t	[41]
Copper	1.64E+05	MJ/t	4.70E+00	tCO_2-eq/t	[14]
Aluminum	2.08E+05	MJ/t	1.60E+00	tCO_2-eq/t	[42]
Polyester	4.57E+04	MJ/t	3.94E+00	tCO_2-eq/t	[41]
Silica	3.06E+04	MJ/t	6.00E−01	tCO_2-eq/t	[14]
Diesel	4.27E+04	MJ/t	3.11E+00	tCO_2-eq/t	[43]
Gasoline	4.31E+04	MJ/t	3.15E+00	tCO_2-eq/t	[43]
Electricity	3.60E+00	MJ/kW h	2.80E−01	tCO_2-eq/MW h	[43]
Fresh water	1.33E+03	MJ/t	4.00E−02	tCO_2-eq/t	[14]

Fig. 5. Embodied energy input in different phases.

and galvanized steel elements, and components and materials of the nacelle include steel, copper, aluminium, glass and unsaturated polyester resin. The rotor is mainly composed of steel, fiberglass and epoxy resin. The major components of the turbines are listed in Table 3.

The transformer substation is constructed with the purpose of changing voltage and decreasing line loss. For the present case study, a 220 kV step-up transformer is installed. Principal components of the building works include wind turbine foundations, transformer foundations, and building works of the distribution equipment. Materials used in construction are mainly steel and concrete. Estimated peak daily water consumption is 400 m^3/d, of which 360 m^3/d is used for production and fire control, and 40 m^3/d for household activities. Gasoline and diesel consumed in the construction phase are 1.67E+05 L and 5.36E+05 L, respectively, and electricity consumption is 1.65E+06 kW h. The materials used in the building works are summarized in Table 4.

3.2.3. Operation

Energy used in the operation phase includes gasoline, electricity and groundwater. Annual gasoline consumption is 5.8 t and electricity consumption 3.32 million kW h, which is mainly consumed by electrical losses in the power generation and transmission system, and is deducted from the calculation of total electricity production. The fresh water required annually is 438 t. During the average useful life of a wind generator, one blade and 15% of generator components are presumed to be substituted [13].

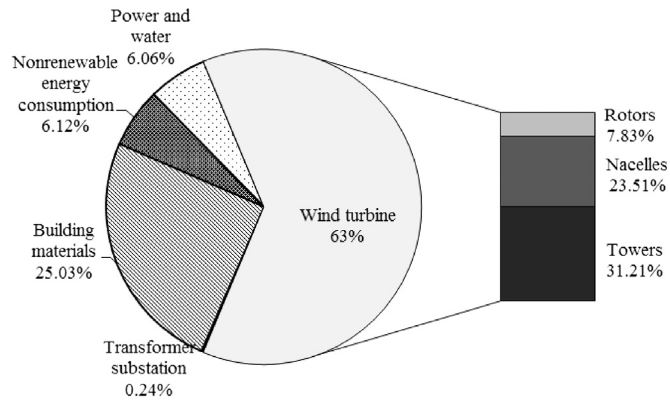

Fig. 6. Energy input embodied in different materials.

3.2.4. Dismantling

Many wind farms have been built in China in recent years, and almost no farms have been dismantled. Since no detailed data on wind farm disposal is available, a principle from Kabir et al. regarding material disposal and recycling of wind turbines was used (Table 5).

3.3. Data sources

The embodied energy and GHG intensity of major materials are listed in Table 6. Detailed inventory data on equipment manufacturing and wind farm construction and operation were derived from sources provided by the developer, China Xiehe Wind Power Investment Co., Ltd.

4. Results and discussion

4.1. Embodied energy performance

Results show that nonrenewable energy consumption embodied in the transportation, construction, and operation phases is 5.10×10^8 MJ. Taking the wind farm dismantling into consideration, the recycled materials will be used to replace the original raw materials in future turbine manufacturing. Thus, material recycling contributes significantly to energy saving, as shown in Fig. 5. The energy saved by material recycling is 2.38×10^8 MJ. If we deduct this part of energy input, total energy invested in the wind farm is 2.72×10^8 MJ. Electricity generated by the wind farm is 183.5 GW h per year. Deducting generation and transmission losses, actual electricity output to the grid is 111.7 GW h per year. Therefore, multiplied by the energy intensity of electricity, total energy output of the wind farm is calculated at 8.04×10^9 MJ over the 20-year operational lifetime.

In that lifetime (Fig. 5), material of the construction phase contributes most to the total energy input, with a value of 88.4%. This is followed by the operational phase, which requires large amounts of gasoline, water and equipment for maintenance. The proportion of energy input in the transportation phase to total energy input is very small, 0.39%. In the dismantling phase, 46.7% of total energy input is recycled and reused.

The results of embodied energy input shows that wind turbines (62.55%) and building materials (25.03%) are the two largest contributors, which together represent 87.58% of total energy cost of the wind farm (Fig. 6). Nonrenewable energy consumption and power and water supply have proportions 6.12% and 6.06%, respectively. Energy embodied in the transformer substation makes up the smallest proportion. For wind turbine components, the proportions of embodied energy of rotors, nacelles and towers are 12.51%, 37.59% and 49.91%, respectively.

4.2. GHG emission accounting

The total GHG emission of the transportation, construction, and operation stages is 2.55E+04 tCO_2-equivalent. When taking dismantling into consideration, the GHG emission should exclude the emission avoided by material recycling and is calculated to be 1.60E+04 tCO_2-equivalent. Fig. 7 illustrates GHG emission in various phases of the wind farm lifetime. Because of wind turbine installation and use of steel and other energy-intensive materials, the construction phase makes up the largest proportion of GHG emission. The operational phase is the second largest contributor of GHG emission. Transportation makes up the smallest proportion at 0.56%, which is mainly caused by diesel consumption.

GHG emission from different inputs is depicted in Fig. 8. Emission from the wind turbines constitutes the largest proportion, at 46.86%. Building materials, especially steel, are second source of GHG emission. Emission from nonrenewable energy consumption and power and water supply constitute 8.91% and 7.43% of total emission, respectively. The transformer station is the smallest contributor. For wind turbines, the GHG emission of towers has the largest proportion at 54.86%, and emissions from nacelles and rotors contribute 35.68% and 9.47%, respectively.

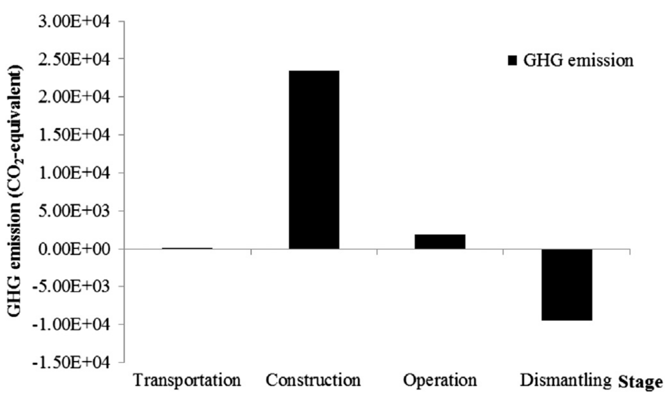

Fig. 7. GHG emissions in different phases.

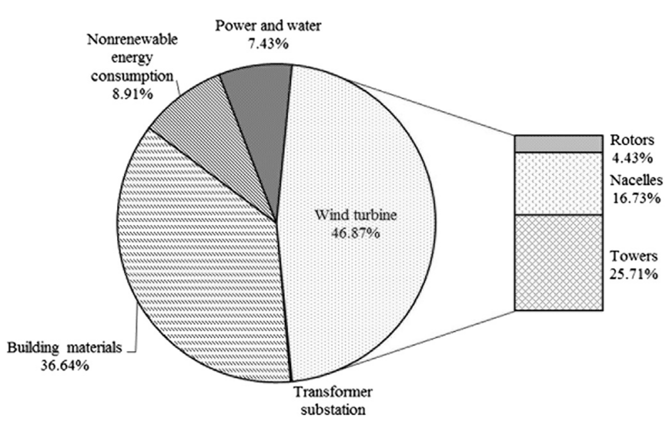

Fig. 8. GHG emissions from different inputs.

4.3. Economic performance

The expected lifetime of the studied wind farm is 21 years, of which the construction period is 12 months and operation is 20 years. It is roughly estimated that the total static investment is \$69.11 million. When interest of the construction investment is taken into consideration, the total dynamic investment is \$70.98 million. In addition, an operating fund of \$0.16 million should be included. Thus, total investment is \$71.14 million.

Fig. 9 shows that investment in the principal part of the project is \$67.69 million, of which costs of the wind turbines, transformer substation, building works and other activities constitute 69.77%, 6.71%, 14.69% and 8.83%, respectively. Obviously, investments in wind turbine equipment make up the largest proportion. It is thus concluded that fluctuations of wind turbine price have the strongest influence on economic indicators.

The electricity connected to the grid is 111.7 GW h, and the benchmark electricity tariff is \$0.088 per kW h in Inner Mongolia. Based on the cost and benefit data series, net economic profit is therefore calculated at \$2.80 million, reinforcing the common consensus that wind power is economically attractive.

Both governments and developers are taking powerful measures to foster development of the wind power industry, and to solve difficulties in attracting investment. Specifically, executing the CDM program, raising wind power prices, and government subsidies are regarded as the most efficient approaches for ensuring that wind power engineering is profitable. Net economic profit of four scenarios, baseline, subsidy, CDM and raising power price scenarios, were thereby established and analysed. The results are listed in Table 7.

Taking into account a subsidy of \$0.036 per kW h announced by the China Development and Reform Commission in 2009, net economic profit would be \$39.2 million, which is 14 times greater than that of the baseline.

As a type of clean energy source, the substitution of wind power for traditional fossil fuel-based thermal power may reduce

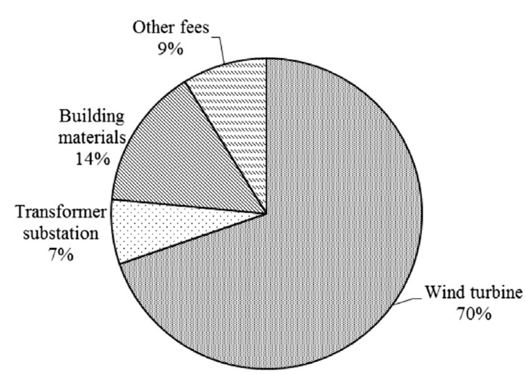

Fig. 9. The economic costs of the wind farm.

Table 7
Net economic profit of different scenarios.

Scenario	Setting	Net economic profit (million \$)
Baseline	Electricity tariff is \$0.088 per kW h	2.80
Subsidy	A subsidy of \$ 0.036 is given per kW h	39.2
CDM	A CDM program is taken for the wind farm	17.7
Raising power price	The price of on-grid power increased by 5% to 10%	7.48–12.2

CO_2 emission. The CO_2 emission reduced by the substitution of wind power is estimated at 127.4 thousand tons. With implementation of a CDM program, the reduced CO_2 emission can be transferred at a price of $11.03/t. The net economic profit is thereby $17.7 million, which is greater than the baseline but less than the subsidy scenario. Consequently, a CDM is considered another alternative for making wind power more attractive.

An increase of wind power price can also increase net economic profit relative to the baseline scenario, as shown in Table 7. Compared with the CDM and subsidy scenarios, however, the effect on net economic profit increase is not outstanding. Moreover, local power grids and the Price Bureau cannot usually accept a relatively high power price. Therefore, there will still be a long way off before the wind power price is raised. In conclusion, the CDM program and government subsidies are regarded as appropriate incentives in promoting wind power programs, from the perspectives of both government and investor.

4.4. Integrated evaluation

The indicators reflecting embodied energy, GHG and economic performance were calculated, and are presented in Table 8. *MRR*of the wind farm is 0.467, indicating that when material recycling of wind turbines is considered, almost half the embodied energy input will be avoided. *IRR* is 9%, larger than that of the average 8% of Chinese society, implying that the economic resource allocation efficiency of this project is at an acceptable level [44].

Compared with other power generation systems such as thermal power plants and other renewable power generation systems, wind power is highly advantageous in terms of energy efficiency and GHG emission reduction (Table 9). *EE* of a wind farm is much smaller than those of solar thermal power plants, solar PV power plants, or traditional coal- or oil-based thermal power plants. Similarly, *ECD* of wind farms is less than that of other power generation systems, which indicates that wind power is promising in terms of both creating a clean energy structure and controlling GHG emission.

Here, the two systematic evaluation indicators, *EI* and *CI*, are defined as the ratio of the embodied energy cost (actual CO_2 released) and net economic profit, which can be used as a numeraire or goal function to account for the trade off between the energy efficiency (low-carbon optimization) level and economic feasibility of the production system. The higher the EI, the higher the energy costs in converting wind energy into profit. The higher the CI, the more the GHG emitted, in the context of economic profitability. The EI and CI are thus determined at 97.261 (MJ/$) and 5.722 (kg$CO_2$-eq/$), respectively.

Since wind power is determined by wind velocity, there may be an unexpected surge of on-grid wind power or sudden breakdown of wind turbines with wind velocity change. The stability of grid system voltage and frequency will thereby be affected when large-scale wind power is connected. Thus, for every MW of installed wind power, a "reserve capacity" must be maintained to overcome instability of wind-power generation and enhance grid reliability. We incorporated this reserve capacity into the accounting framework. In China, no separate reserve capacity is built in for a wind farm to balance wind power supply load, and the existing spinning thermal power capacity reserve in the power grid system is used for maintaining wind power stability. Following Yu et al. [49], assuming the loss of load probability (LOLP) and equivalent forced outage rate (EFOR) are 0.00125 and 0.15321, respectively, 1 MW of wind power connected to the grid brings about an increase of 0.80 MW reserve capacity within a grid system. Based on the parameters in Table 10, an integrated analysis of the wind farm with reserve capacity was conducted. For economic analysis, investment in generator capacity is required, and the cost of maintaining spinning reserve is considered. GHG emissions and embodied energy are considered based on electricity generated by the reserve capacity, which is used to power up when wind speed drops.

Incorporating the reserve capacity into the proposed evaluation framework, *MRR*, *EE*, *ECD*, *EI*, *CI* and *IRR* are calculated at 0.466 MJ/MJ, 0.034 MJ/MJ, 0.002 kgCO_2-eq/MJ, 99.130 MJ/$, 6.041 kg$CO_2$-eq/$ and 9%, respectively. Compared with the results in Table 8, adding reserve capacity has little impact on energy and GHG emission, as well as economic performance of the wind farm (reflected by *MRR*, *EE*, *ECD* and *IRR*). This is because the on-grid capacity of this farm and operational hours of the reserve capacity used for balancing wind power generation are small in a grid system. However, there is prominent change of *EI* and *CI*, which increase by 1.869 MJ/$ and 0.319 kgCO_2-eq/$. This implies that although the impact of reserve capacity is not obvious, energy intensity and GHG emission intensity increased because of less monetary benefit and more energy input (GHG emission).

5. Conclusions

In this paper, we assessed embodied energy, GHG emission, and economic performance of a Chinese wind farm through

Table 8
The values of energy, GHG emission, and economic evaluation indicators.

Indicator	*MRR*	*EE*	*ECD*	*EI*	*CI*	*IRR*
Value	0.467	0.034	0.002	97.261	5.722	9.000
Unit	MJ/MJ	MJ/MJ	kgCO_2-eq/MJ	MJ/$	kgCO_2-eq/$	%

Table 10
Parameters of reserve capacity provided for the wind farm.

Parameter	Value	Parameter	Value
Reserve capacity	39.6 MW	Lifetime	20 years
LOLP	0.00125	Reserve capacity cost	18.267 $/MW [50]
EFOR	0.15321	Thermal power price	45.668 $/MW h [50]

Table 9
Energy and GHG emission intensities of different power generating systems.

Turbine	Location	Year	*EE* (MJ/MJ)	*ECD* (kgCO_2-eq/MJ)	References
Wind farm with the installed capacity of 49.5 MW	Inner Mongolia, China	2011	0.034	0.002	This paper
Wind farm with the installed capacity of 1.25 MW	Guangxi, China	2010	0.047	0.002	[14]
2.7 kWp distributed solar PV system	Singapore	2006	0.803	0.060	[45]
1.5 MW solar thermal power plant	Yanqing, China	2011	0.950	0.040	[46]
Coal based thermal power plant	Italy	2002	4.000	0.309	[47]
Oil based thermal power plant	Italy	2002	3.340	0.257	[47]
Hydropower plant	The world	2009	–	0.001–0.065	[48]

a proposed evaluation framework with a series of indicators. New indicators of energy intensity and GHG emission intensity, defined as energy and GHG emission cost per unit profit, were proposed to present a new goal function for potential low-carbon, high-efficiency optimization of the wind power generation system.

From the embodied energy use and GHG emission perspectives, compared with other electricity generation systems, it is clear that wind power is a good choice for both energy savings and GHG emission reduction. Over the wind farm lifetime, GHG emitted from the building works and wind turbines contributes most of the total emissions. This indicates that material input is the component that most affects the environment, among which steel components are the source of GHG emission. Thus, manufacturers should pay attention to optimization of manufacturing processes in order to qualify for an eco-label. It is also promising to look more closely into means of material recycling and reusing building materials, which can greatly contribute to both energy savings and GHG reduction.

The overall results of the present economic feasibility analysis indicate that the wind power generation program is profitable. Moreover, from the standpoint of investors, additional benefits can be gained from CDM programs that trade the CO_2 emissions reduced by the wind farm. Regarding government incentives, government subsidies of wind power can maximize profit and are therefore the most effective means to attract more investment in wind power, in turn promoting rapid development of the wind power industry.

By considering a reserve capacity used to compensate the instability caused by wind power connection, there is only minor variation of energy and GHG emission intensities, owing to greater energy (GHG) input and less economic benefit. However, this paper presents only a preliminary estimation. The structure of reserve capacity (thermal or hydro) provided by a grid system, operational hours of the reserve capacity for wind power peak load regulation, reserve capacity required per MW of wind power production, and others, should be further investigated to improve accuracy.

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